PAPER • **OPEN ACCESS**

Decarbonisation of the urban built environment through vegetation-based carbon sequestration

To cite this article: K Varshney *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1101** 062025

Decarbonisation of the urban built environment through vegetation-based carbon sequestration

K Varshney[1]*, M P Zari[2] and N Bakshi[1]

[1] School of Architecture, Victoria University of Wellington, Aotearoa New Zealand

[2] School of Future Environments, Auckland University of Technology, Aotearoa New Zealand

*Corresponding author email: kamiya.varshney@vuw.ac.nz

Abstract. The impacts of climate change require a strategic improvement in design decision-making. Leading professionals are aiming for carbon-positive buildings that can achieve carbon sequestration by adding vegetation to buildings. Multiple references and case studies explored in this paper suggest that there is theoretical potential for cities to become carbon sinks by constructing carbon-positive buildings. However, determining effective strategies, and quantifying and monitoring carbon sequestration in buildings, requires a standardised approach so that this carbon sequestration potential can be measurably established. This paper provides two key outputs: firstly, the paper identifies strategies that could shift buildings towards being capable of active carbon sequestration. Secondly, the paper provides a methodological framework with four key considerations that building professionals can use to design for carbon sequestration. These are: understanding the site's ecological, climatic, cultural and legal context; identifying response, pressure, state and benefits indicators to set carbon sequestration targets; considering site ecosystem functioning and carbon dynamics to strategise carbon sequestration through design; and preparing long-term monitoring, evaluation and management plans. This paper identifies two areas for further investigation: linking manual quantification methods with computer-aided methods; and utilising biomass data and growth models at the landscape, regional, and global levels for carbon sequestration assessment.

1. Introduction

Approximately 55% of the world's population resides in urban areas, which is expected to rise to 68% by 2050 [1]. With this rise in urban population, urban areas are also expanding. There are numerous consequences of rapid urbanisation and urban growth, including changes in land use and land cover, which directly or indirectly contribute to climate change and biodiversity loss [2]. Furthermore, the urban built environment is one of the most significant contributors to greenhouse gas (GHG) emissions and accounts for approximately 38% of annual global carbon emissions [3, 4]. It should be recognised that the built environment plays a critical role in preventing global temperature rise beyond the Paris Agreement's 1.5°C [5]. Several countries have introduced targets to achieve net-zero emissions by 2050 [3, 6]; in that regard, the building sector is also focusing on strategies to achieve lower embodied and operational emissions or net-zero emissions. The United Nations Environment Programme (UNEP) global status report for building and construction states, *"Using the mean across all scenarios modelled by Climate Action Tracker [6], the total direct CO_2 emissions reductions from the [building] sector should be at least 45% by 2030, 65% by 2040, and 75% by 2050 relative to 2020"* [3]. Therefore, it is well-understood that the faster countries decarbonise, the higher the probability of reaching net-zero emissions by 2050 and of limiting peak warming to 1.5°C [7].

Often built environment professionals implement strategies to reduce carbon emissions and use renewable energy sources as a response to climate change mitigation agendas. However, instead of minimising the negative impacts or targeting net-zero, there is a need to shift the focus toward regenerative goals or net-positive goals, and from carbon emission reduction to net-positive carbon buildings [8-11]. Renger et al. [12] showed that a building could sequester more carbon over its life cycle than it emits by using onsite renewable energy technology and extensive building-integrated vegetation; and, therefore, could contribute to net-positive carbon storage. The process of actively capturing carbon dioxide from the atmosphere through the growth of vegetation is known as carbon sequestration (biotic). Refer to Varshney et al. [13] for a detailed definition of carbon sequestration and to understand the carbon sequestration process through building-integrated vegetation, i.e., through trees, grass, and soil. There is significant literature regarding building materials that store carbon and can, therefore, offset the embodied and operational carbon emissions over the longer term [14-16]. However, the research reported on here is limited to vegetation-based carbon sequestration. Figure 1 represents a conceptual diagram to strategise the decarbonisation of the urban built environment, where the dotted circle highlights the research area.

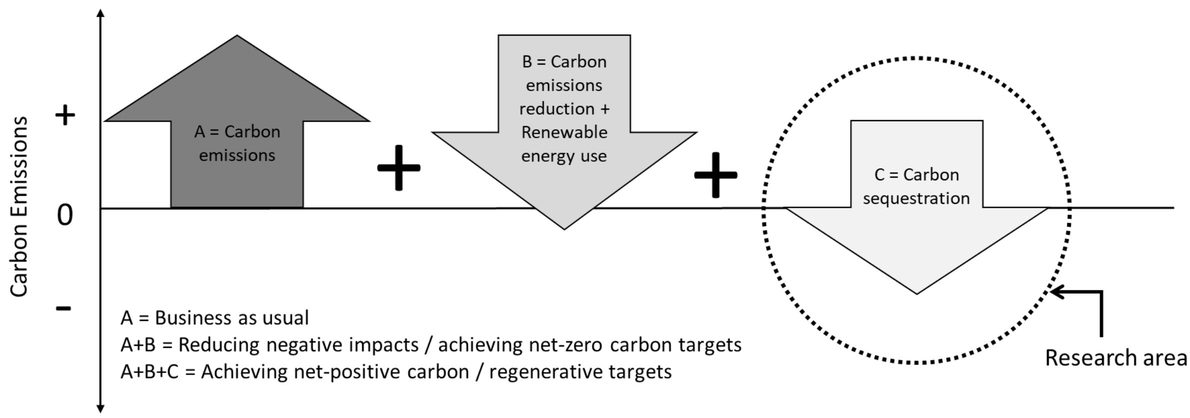

Figure 1. Strategising decarbonisation of the urban built environment: research area highlighted
Source: Adapted from Deo Prasad, Kuru [17], p. 17

Long-term carbon removal through sequestration by strategically planting vegetation is an anthropogenically driven natural process to help decarbonise the urban built environment [12, 18]. Studies suggest that domestic gardens in urban centres have greater soil organic carbon (SOC) concentrations and, therefore, more carbon stocks compared to non-domestic urban green spaces [19]. Furthermore, Davies et al. [20] suggested that even within a typical dense urbanised city centre, urban vegetation has the potential to offset embodied and operational carbon emissions by sequestering and storing carbon. Zirkle et al. [21] compared lawn, landscape and forest annual carbon sequestration rates and demonstrated that lawns and landscapes could sequester carbon dioxide at a rate equal to a natural forest stock. Moreover, they concluded that trees store most of the carbon above ground in wood and grassed areas store most of the carbon below ground in the soil.

This research has two main objectives. The first objective is to know *what* strategies could be employed to increase the green vegetative space and create a permanent canopy for active carbon sequestration through building design. The second objective is to know *how* those strategies could be implemented; therefore, to provide a methodological framework that building professionals can adopt while designing. Because there has been little research available on vegetation-based carbon sequestration at a building scale, the aim is to fill the gaps by reviewing landscape level to urban forest sequestration studies that underpin the objectives of this research. For this purpose, ecological studies concerning ecosystem functioning were analysed and then translated into the built environment context. The literature review was undertaken to determine strategies and methodological frameworks that contribute to active carbon sequestration in urban settings. The criterion for preparing the methodological framework is to create simple procedural guidelines that the building professionals could easily apply into building design.

2. Vegetation-based carbon sequestration strategies

Nature-based solutions, ecological design, and regenerative design are new paradigms that designers and decision-makers are employing to accentuate health and wellbeing co-benefits for humans and ecosystems. Carbon sequestration is one such strategy that strengthens these paradigms and could synergistically contribute to increased biodiversity and climate change mitigation and adaptation agendas [12, 22]. The commonly used strategies to sequester carbon through building-integrated vegetation were determined by a systematic literature review. They are as follows:

2.1. Conserving existing urban biodiversity

Carbon is sequestered and stored in the above-ground biomass of stems, leaves, and branches; and below-ground biomass of roots and soil. As the tree matures, tree density, leaf area index (LAI), canopy coverage, and root mass increase proportionately in the form of carbon stocks [23]. Urban biodiversity and indigenous vegetation are part of the living space of the urban dwellers. Preserving indigenous vegetation is one of the strategies to conserve urban biodiversity while planning and designing for urban development. Therefore, it is important to assess and recommend strategies to conserve existing vegetation by identifying ecological functions and connectivity, and representing the ecological potential of safeguarding the existing flora and fauna [24].

2.2. Adding vegetation on and around buildings

Building-integrated forests could increase the vegetated area of cities by utilising horizontal and vertical surface areas of a building, and therefore, increasing carbon stock within urban space and land-use limitations [12, 25]. Strategies to add vegetation to buildings include green walls, green roofs, internal courtyards/atriums, in-ground landscaping, urban agriculture, indoor gardens and living machines (Figure 2).

Figure 2. Increasing ecological area by integrating vegetation on and around buildings
Source (Left): Apartment building; CC0 1.0, (Right): Rod Waddington, CC BY-SA 2.0

2.3. Vegetation species selection

Another important strategy is to select vegetation species based on their carbon sequestration rates for above- and below-ground biomass. Several approaches for species selection that significantly enhance carbon sequestration rates are: increase woody biomass longevity; increase pest and disease resistance; improve photosynthetic efficiency; consider growing seasons of plants; increase root: shoot ratios; and improve water efficiency, nutrient utilisation, salt tolerance and pH tolerance [21, 26]. Carbon sequestration in urban areas and/or residential landscapes is often calculated based on the vegetated area coverage multiplied by per square meter carbon sequestration rates [21, 27]. However, this method does not consider the dynamics of carbon sequestration rates. Therefore, scientific and research-based data on species selection and the aforementioned strategies are required to improve the carbon sequestration rates [28].

2.4. Amending abiotic conditions to maximise carbon sequestration rates

The abiotic conditions; such as soil composition, fertility and depth, water quality and availability, temperature, sunlight availability, and wind and air quality; regulate and influence carbon sequestration rates [21]. Therefore, strategies for increasing carbon sequestration rates revolve around improving the abiotic conditions that support and maximise carbon stocks in building-integrated vegetation. Waste byproducts (such as fly ash, sewage sludge and biochar) could be used to improve soil characteristics for maximising carbon sequestration [26, 29] and simultaneously could be a climate change mitigation strategy [30]. According to Razzaghi et al. [31], adding biochar to the course- or medium-textured soil can increase the water retention capacity. Strategies to retain soil organic carbon (SOC) and soil inorganic carbon (SIC) include mineral carbonation and the addition of black carbon to the subsoil layer [32].

2.5. Post-occupancy maintenance and management strategies

Net-carbon sequestration is the difference between the amount of carbon absorbed through photosynthesis and released through respiration, decomposition, deforestation and other management practices [33]. Therefore, it is essential to maintain and improve existing tree health to maximise sequestration and minimise mortality losses or decomposition. Moreover, the relation between lifetime analysis of maintenance requirements and long-term carbon storage needs to be focused on while targeting net-positive carbon sequestration goals. The higher the level of management of vegetation and lawns, the higher the hidden carbon cost (HCC) related to fertilisation, pest control, mowing and irrigation, and the lesser the net-carbon sequestration rate [34]. Strategies to minimise water requirements and/or greywater use for irrigation reduce carbon emissions (and HCC), thus improving carbon sequestration rates [35]. Monitoring and reporting of carbon sequestration strategies, accounting for both carbon emissions and sequestration, are essential to designing more efficient and effective solutions for carbon management. For example, trees require energy inputs during establishment, maintenance (pruning, site prep, fertiliser, leaf litter, chipping, and/or transport) and disposal; however, trees offset the energy that would be required for cooling buildings if they were not present through shading, evapo-transpirative cooling and reducing the heat-island effect [26].

3. A methodological framework for implementing carbon sequestration strategies

Outlining how designers can practically implement carbon sequestration strategies defined in section 2 is the focus of this section. Existing frameworks for design and decision-making concerning regenerative architecture were analysed to prepare a crafted methodological framework for carbon sequestration considerations. The key regenerative frameworks reviewed were: society for ecological restoration [36], regenerative development and design: a framework for evolving sustainability [37], the ecosystem services analysis [10], and net-positive design and sustainable urban development [9]. Moreover, carbon sequestration assessment methods from the literature were reviewed in order to integrate them into the regenerative design framework. The key assessment methods reviewed were: net-positive building carbon sequestration [12], carbon sequestration through urban ecosystem services [27], modelling carbon sequestration in the U.S. residential landscape [21] and mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale [20]. Assessment methods that evaluate carbon sequestration for a neighbourhood and/or city level were also studied. Based on this literature review, a methodological framework was prepared that can be adapted to different ecological, climatic, cultural and legal contexts. Figure 3 summarises the carbon sequestration methodological framework.

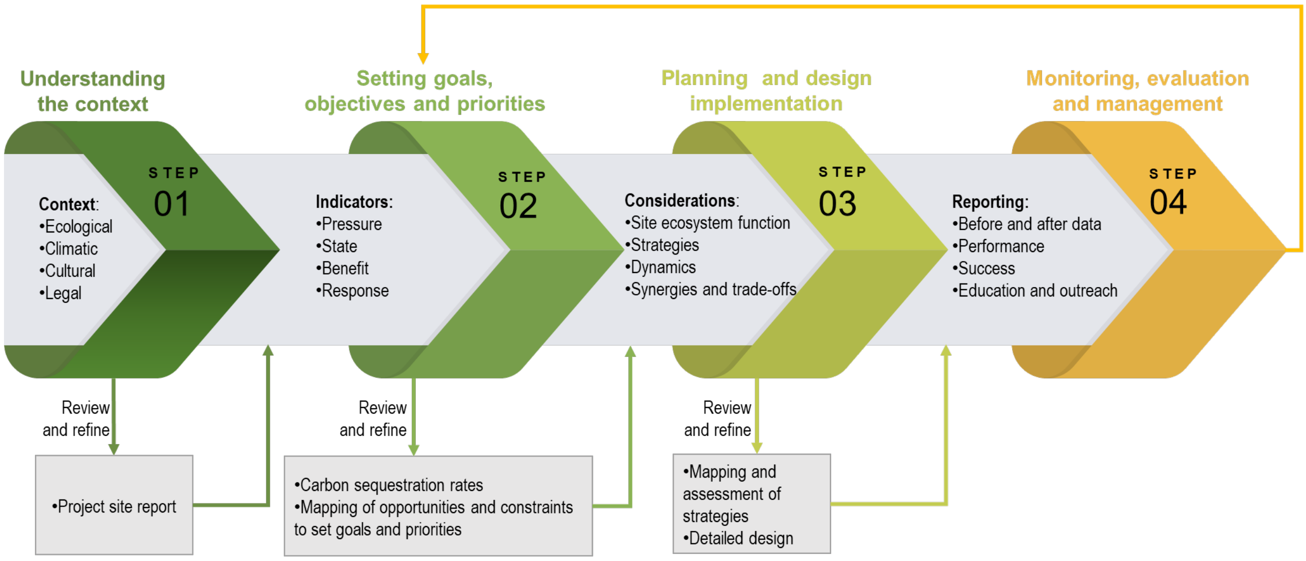

Figure 3. Carbon sequestration methodological framework

3.1. Step 1: Understanding the context, identifying issues, and setting out the conditions, constraints and opportunities

The first step is to understand the site context and its surroundings. For this purpose, it is crucial to analyse the site's current and predevelopment ecological, climatic, cultural and legal contexts [10, 36]. The current and retrospective analysis will provide a basis for setting the prospective regenerative targets or carbon sequestration goals.

- *Predevelopment and existing ecology*: Study the ecological history and existing ecology of the site and analyse the current and historical data for biotic (indigenous and exotic species at the site, species composition) and abiotic components (soil type, topography, habitat types, natural resources, and water availability and quality) through historical and current maps, the survey of existing conditions (natural and built), Geographical Information System (GIS) mapping, photographs, and other representations of areas (sketches, for example). The abiotic conditions of the site play a significant role in being able to select appropriate vegetation species and to know how to employ them to enhance carbon sequestration rates. Moreover, this step calls for monitoring and evaluation of the drivers of degradation of ecosystems or ecological stressors on or nearby the project site. Such analysis suggests which interventions are required to regenerate the degraded ecosystem and understand the capacity for eventual self-organisation or enhanced resilience to future stresses [36].
- *Climatic context*: Study the current climatic conditions, weather patterns, precipitation, wind and sunlight for the region and analyse the microclimate of the site, including: ventilation factors, solar radiation, sun path, temperature, slope, shading, and heat island considerations. This climate data will help to determine strategies that support vegetation to thrive. This data is typically available for most regions through weather information websites. Moreover, this step calls for the analysis of current and potential future climate change impacts in order to determine appropriate vegetation species and conditions.
- *Cultural ecologies*: Study cultural and local practices for maintaining native ecosystems and working with climate. These management strategies will help to design a unique regenerative built environment system mimicking traditional cultural understandings of how to live in a particular environment. The data could be collected through participatory design approaches, interviews, literature review, consultation, and expert judgement. Cultural intelligence or knowledge and time to build relationships with local peoples are typically required for this step.
- *Legal obligations*: Study the local legal obligations, rules, policies, recommendations, or regulatory protection mechanisms for the site and /or nearby sites of ecological significance to

safeguard native vegetation and biodiversity. Policies and guidelines specific to that region are typically available on local government websites.

The output of this step is the *Project/site report*, which includes conditions, constraints, and opportunities concerning carbon sequestration. This report underpins the following step to establish carbon sequestration goals, objectives and priorities.

3.2. Step 2: Setting carbon sequestration goals, objectives and priorities

This second step is to select a core set of indicators for quantitative assessment. Once the measurement criteria are set, the next step is to evaluate existing carbon sequestration provision on site. Subsequently, the goals, objectives, and priorities for carbon sequestration through building design can be set based on results from the site evaluation.

Pressure, state, benefits, and response indicators should be established to evaluate the current state of the site and to set the regenerative goals [38, 39]. Moreover, their measurement method in the context of decarbonising the built environment through building-integrated vegetation should be determined.

- *Pressure indicators* monitor the extent and intensity of the causes of climate change that responses aim to address, e.g. carbon emissions.
- *State indicators* analyse the condition and status of the aspects of carbon sequestration, e.g., above-ground and below-ground biomass. Allometric equations [40], modelling approaches [21], and/or ecosystem services assessment tools (ESAT) [41, 42] can be used to measure these indicators.
- *Benefits indicators* quantify the benefits from anthropogenically driven vegetation-based carbon sequestration, e.g., the amount of carbon sequestered per year and improved biodiversity.
- *Response indicators* measure the implementation of policies or actions to prevent or reduce carbon emissions and remove atmospheric carbon (if any), e.g., net-zero carbon policy by 2050.

Evaluate carbon sequestration rates as the baseline using the above data to help set the goals and priorities for long-term carbon sequestration over time. Furthermore, map all the opportunities and limitations/constraints to set goals and priorities in stages.

3.3. Step 3: Planning and design implementation

In this step, utilise the goals and priorities set in step 2 to prepare the concept plans and alternatives and further develop and refine detailed designs. The following inputs required for carbon sequestration designing are analysed to prepare the concept and detailed plans:

- *Site ecosystem functions*: It is essential to analyse site ecosystem functions, such as species dependencies and interactions. The ecosystem functions and services analyses, along with carbon sequestration goals, will help to design for regenerative targets strategically, e.g., reintroducing carbon sequestration ecosystem services that may be absent in urban areas due to conventional ways of constructing urban environments, i.e. with mostly impervious and non-living materials [10].
- *Carbon sequestration strategies*: Strategies identified in section 2 could be employed and analysed with respect to site-specific solutions. Understanding the role of indigenous (native) and exotic (non-native) species in terms of their carbon sequestration rates is crucial. Evaluating the appropriateness of the identified strategies and their contribution to improving carbon sequestration rates is required. Moreover, assessing the short-term and long-term benefits of employing those strategies in the building design must be completed.
- *Carbon sequestration dynamics*: Carbon sequestration through building-integrated vegetation could be improved by identifying and analysing the dynamics of biotic and abiotic components. For example, the phenological stage of a plant (young or mature) and its required growing conditions (water, nutrient, and sunlight availability) significantly affect net-carbon sequestration rates over a plant's lifetime [21].
- *Synergies and trade-offs with other ecosystem services*: Synergies and trade-offs are essential to identify because they play a significant role in preparing an integrated approach toward regenerative development. Synergies provide long-term compatible solutions by symbiotically

benefitting or (re)generating two or more ecosystem services. Trade-offs indicate the limitations of the proposed strategies; that is, how increasing one ecosystem service could negatively affect others. When trade-offs are identified, careful considerations must be taken regarding whether to mitigate or offset the impacts or avoid them altogether [43].

The final part of step 3 is to map and assess the design strategies with respect to carbon sequestration rates in order to achieve positive-carbon targets. This mapping and assessment, along with the comparison of alternatives, will help to determine detailed designs. Detailed designs must be continuously reviewed and refined with involvement and suggestions from indigenous landowners, other stakeholders, and policymakers.

3.4. Step 4: Monitoring, evaluation and management

This step identifies methods to monitor likely changes in species, structure, and functionality of building integrated vegetation over short, medium and long-term regenerative targets. Considering the dynamic nature of ecosystems or smaller plant communities, as they continue to adapt and evolve in response to anthropogenic interventions, climate change, and degrading ecological conditions, it is essential to monitor carbon sequestration rates over time [36]. This requires short-, medium- and long-term management plans and re-evaluation of response, pressure, state and benefits indicators across the measurable goals and objectives determined in step 2. This monitoring and evaluation identify the future need for adaptive management [36]. Monitoring, evaluation and management planning must be included in the pre-design and design stages to ensure that the goals considered are measurable and achievable. Photographic (time-series) and quantitative tools (indicators) could be used to monitor the performance and success of the project prior to commencement and at regular intervals subsequent to development to show changes over time. The final part of step 4 is to prepare outreach and educational programmes for the building occupants, and neighbours in relation to the management of vegetation on and around the building at pre-design and design stages.

4. Findings and Discussion

This research had two main objectives. Section 2 presented broad strategies that can be implemented for vegetation-based carbon sequestration in a building design. Section 3 presented a methodological framework that building professionals could adopt to implement building-integrated carbon sequestration strategies suitable for different climatic, ecological, cultural, and legal contexts. Section 3 also includes linking of strategies given in section 2 to the framework. The methodological framework is flexible and straightforward and could be updated as new information is received.

There are two significant gaps in the research area. The first gap relates to assessing carbon sequestration rates, i.e., linking manual quantification methods with computer-aided simulation methods specific to the built environment context. Ecosystem services assessment tools available are often applied to a neighbourhood, city, or regional level rather than a single site. This linking will improve the ability to measure and verify net carbon sequestration and expedite the process of quantification. However, the robustness of the computer-aided methods must be evaluated by regular updating in terms of indicators and carbon sequestration dynamics and 'ground-truthing' fieldwork. The second gap is the resource availability of biomass data and vegetation growth models at the landscape, regional, and global levels that could be utilised for rapid net carbon sequestration assessment. Global carbon pool data is available for biotic, oceanic, geologic and pedologic carbon sequestration [33]. However, the availability of carbon sequestration data (based on present ecological and climatic conditions) at a landscape or neighbourhood scale is still needed. This data would further facilitate the design process for net-positive carbon urban development.

5. Conclusions and further research

The built environment is one of the most significant sources of carbon emissions, but it could become a sink of atmospheric carbon if strategic design occurs. This would be based on total carbon management, including reducing GHG emissions, offsetting GHG emissions with renewable energy generation, and increasing vegetation-based carbon sequestration. A significant contribution from the building sector is required to achieve the ambitious climate policy target of limiting global average temperature warming to 1.5°C in line with the 2015 Paris Agreement. Green spaces on and around buildings have significant potential to sequester and store carbon in their biomass (including the soil). However, while implementing carbon sequestration strategies in building design, carbon emissions from the provisioning of those strategies must also be considered across whole life cycles. The amount of sequestered carbon varies within different parameters, and therefore, careful consideration must be taken concerning carbon sequestration dynamics to make building-integrated vegetation design as effective as possible. A biological understanding of carbon sequestration processes and ecosystem functions can help to guide the selection of appropriate strategies for building-integrated vegetation-based carbon sequestration.

The research reported here is part of a larger research project. The next stage of this research includes further developing and refining this proposed methodological framework by conducting surveys and interviews with architects, sustainability consultants, ecologists, academic researchers and other design professionals. Furthermore, the refined methodological framework will be tested on a site evaluating the probability of success in achieving carbon-positive buildings. This research aims to illustrate the positive impact potential of strategic vegetation-based carbon sequestration as part of the wider strategy of decarbonising the urban built environment. To conclude, carbon sequestration through building-integrated vegetation has multiple co-benefits that could improve ecological health and human wellbeing by increasing biodiversity. Buildings with regenerative performance goals that embrace ecosystem-based approaches have significant potential to enhance urban resilience, biodiversity regeneration, and climate change mitigation and adaptation simultaneously.

6. References

[1] United Nations Department of Economic and Social Affairs Population Division 2019 *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)* (New York: United Nations)

[2] Pörtner H O, Scholes R J, Agard J, Archer E, Arneth A, Bai X, Barnes D, Burrows M, Chan L, Cheung W L, Diamond S, Donatti C, Duarte C, Eisenhauer N, Foden W, Gasalla M A, Handa C, Hickler T, Hoegh-Guldberg O, Ichii K, Jacob U, Insarov G, Kiessling W, Leadley P, Leemans R, Levin L, Lim M, Maharaj S, Managi S, Marquet P A, McElwee P, Midgley G, Oberdorff T, Obura D, Osman E, Pandit R, Pascual U, Pires A P F, Popp A, Reyes-García V, Sankaran M, Settele J, Shin Y J, Sintayehu D W, Smith P, Steiner N, Strassburg B, Sukumar R., Trisos C, Val A L, Wu J, Aldrian E, Parmesan C, Pichs-Madruga R, Roberts D C, Rogers A D, Díaz S, Fischer M, Hashimoto S, Lavorel S, Wu N and Ngo H T 2021 *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change* (Bonn, Germany: IPBES secretariat)

[3] United Nations Environment Programme 2020 *2020 Global status report for buildings and construction: towards a zero-emission, efficient and resilient buildings and construction sector* (Nairobi: UNEP)

[4] International Energy Agency 2020 *World energy outlook 2020* (Paris: OECD Publishing)

[5] Intergovernmental Panel on Climate Change 2014 *Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change* ed Edenhofer O R et al (Cambridge, United Kingdom and New York, USA: Intergovernmental Panel on Climate Change)

[6] Climate Action Tracker 2021 *Evaluation methodology for national net zero targets* Available at https://climateactiontracker.org/publications/evaluation-methodology-for-national-net-zero-targets

[7] Rogelj J, Huppmann D, Krey V, Riahi K, Clarke L, Gidden M, Nicholls Z and Meinshausen M 2019 A new scenario logic for the Paris Agreement long-term temperature goal *Nature* **573** pp 357-363

[8] Mang P and B Reed 2012 Regenerative development and design *Sustainable Built Environments* pp 115-141

[9] Birkeland J 2020 *Net-positive design and sustainable urban development* (New York: Routledge)

[10] Pedersen Zari M 2018 *Regenerative urban design and ecosystem biomimicry* (Abingdon: Routledge)
[11] Cole R J 2012 Transitioning from green to regenerative design *Building Research & Information* **40** pp 39-53
[12] Renger B C, Birkeland J L and Midmore D J 2015 Net-positive building carbon sequestration *Building Research and Information* **43** pp 11-24
[13] Varshney K, Pedersen Zari M and Bakshi N 2022 Carbon sequestration through building-integrated vegetation *The Palgrave Encyclopedia of Urban and Regional Futures* ed Brears R C (eBook: Palgrave Macmillan, Cham)
[14] Reddy M S and S Joshi 2018 Carbon dioxide sequestration on biocement-based composites, in *Carbon Dioxide Sequestration in Cementitious Construction Materials* ed Pacheco-Torgal F et al (eBook: Woodhead Publishing)
[15] Arehart J H, Hart J, Pomponi F and D'Amico B 2021 Carbon sequestration and storage in the built environment *Sustainable Production and Consumption* **27** pp 1047-1063
[16] Kuittinen M, Zernicke C, Slabik S and Hafner A 2021 How can carbon be stored in the built environment? A review of potential options *Architectural Science Review* pp 1-17
[17] Deo Prasad MD, Kuru A, Oldfield P, Ding L, Noller C and He B 2021 *Race to Net Zero Carbon: A Climate Emergency Guide for New and Existing Buildings in Australia* (Australia: Low Carbon Institute)
[18] Shafique M, Xue X and Luo X 2020 An overview of carbon sequestration of green roofs in urban areas *Urban Forestry and Urban Greening* **47** 126515
[19] Edmondson J L, Davies Z G, McCormack S A, Gaston K J, Leake J R 2014 Land-cover effects on soil organic carbon stocks in a European city *Science of The Total Environment* **472** pp 444-453
[20] Davies Z G, Edmondson J L, Heinemeyer A, Leake J R and Gaston K J 2011 Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale *Journal of applied ecology* **48** pp 1125-1134
[21] Zirkle G, Lal R, Augustin B and Follett R 2012 Modeling carbon sequestration in the US residential landscape *Carbon sequestration in urban ecosystems* (Dordrecht: Springer) pp 265-276
[22] Ussiri D A N 2017 *Carbon Sequestration for Climate Change Mitigation and Adaptation* ed. Lal R (Cham: Springer International Publishing)
[23] Abreu R C, Hoffmann W A, Vasconcelos H L, Pilon N A, Rossatto D R and Durigan G 2017 The biodiversity cost of carbon sequestration in tropical savanna *Science advances* **3** 1701284
[24] Breuste J H 2004 Decision making, planning and design for the conservation of indigenous vegetation within urban development *Landscape and urban planning* **68** pp 439-452
[25] Lal R 2012 Towards Greening of Urban Landscape *Carbon Sequestration in Urban Ecosystems* (Dordrecht: Springer) pp 373-383
[26] Reichle D, Houghton J, Kane B and Ekmann J 1999 *Carbon sequestration research and development* (United States: Oak Ridge National Lab)
[27] Kuittinen M, Moinel C and Adalgeirsdottir K 2016 Carbon sequestration through urban ecosystem services: A case study from Finland *Science of the Total Environment* **563** pp 623-632
[28] Agbelade A D and Onyekwelu J C 2020 Tree species diversity, volume yield, biomass and carbon sequestration in urban forests in two Nigerian cities *Urban Ecosystems* **23** pp 957-970
[29] Sarfraz R, Hussain A, Sabir A, Fekih I B, Ditta A and Xing S 2019 Role of biochar and plant growth promoting rhizobacteria to enhance soil carbon sequestration—a review *Environmental monitoring and assessment* **191** pp 1-13
[30] Palumbo A V, Porat I, Phillips J R, Amonette J E, Drake M M, Brown S D and Schadt C W 2009 Leaching of mixtures of biochar and fly ash *Proc. of the World of Coal Ash (WOCA) Conference, Lexington, KY, USA* (United States: Office of Scientific and Technical Information)

[31] Razzaghi F, Obour P B and Arthur E 2020 Does biochar improve soil water retention? A systematic review and meta-analysis *Geoderma* **361** 114055
[32] Lorenz K and Lal R 2015 Managing soil carbon stocks to enhance the resilience of urban ecosystems *Carbon Management* **6** pp 35-50
[33] Lal R 2008 Carbon sequestration *Philosophical Transactions of the Royal Society B: Biological Science* **363** pp 815-830
[34] Zirkle G, Lal R and Augustin B 2011 Modeling carbon sequestration in home lawns *HortScience* **46** pp 808-814
[35] Lecocq F 2001 Optimal use of carbon sequestration in a global climate change strategy : is there a wooden bridge to a clean energy future? ed Chomitz KM *Policy research working papers* (Washington, D.C: World Bank, Development Research Group, Infrastructure and Environment)
[36] McDonald T, Gann G, Jonson J and Dixon K 2016 *International standards for the practice of ecological restoration–including principles and key concepts* (Washington, DC, USA: Society for Ecological Restoration)
[37] Mang P and Haggard B 2016 *Regenerative development and design : a framework for evolving sustainability* ed Haggard B (Hoboken, NJ: Wiley)
[38] OECD 2001 *OECD Environmental Indicators: Towards Sustainable Development 2001* (Paris: OECD Publishing)
[39] Sparks T H, Butchart S H M, Balmford A, Bennun L, Stanwell-Smith D, Walpole M, Bates N R, Bomhard B, Buchanan G M and Chenery A M 2011 Linked indicator sets for addressing biodiversity loss *Oryx* **45** pp 411-419
[40] Aguaron E and McPherson E G 2012 Comparison of methods for estimating carbon dioxide storage by Sacramento's urban forest *Carbon sequestration in urban ecosystems* (Dordrecht-Springer) pp 43-71
[41] Bagstad K J, Semmens D J, Waage S and Winthrop R 2013 A comparative assessment of decision-support tools for ecosystem services quantification and valuation *Ecosystem Services* **5** pp 27-39
[42] Delpy F, Pedersen Zari M, Jackson B, Benavidez R and Westend T 2021 Ecosystem Services Assessment Tools for Regenerative Urban Design in Oceania *Sustainability* **13** 2825
[43] Pedersen Zari M 2021 Biomimetic Urban and Architectural Design: Illustrating and Leveraging Relationships between Ecosystem Services *Biomimetics* **6** 2

Acknowledgements
The corresponding author gratefully acknowledges financial support from the Centre for Biodiversity and Restoration Ecology (CBRE) and a Faculty Research Grant from Victoria University of Wellington for in-person conference attendance.